

Star-to-star Na and O abundance variations along the red giant branch in NGC 2808 ¹

Eugenio Carretta², Angela Bragaglia ², Carla Cacciari²

ABSTRACT

We report for the first time Na and O abundances from high-resolution, high S/N echelle spectra of 20 red giants in NGC 2808, taken as part of the Science Verification program of the FLAMES multi-object spectrograph at the ESO VLT. In these stars, spanning about 3 mag from the red giant branch (RGB) tip, large variations are detected in the abundances of oxygen and sodium, anticorrelated with each other; this is a well known evidence of proton-capture reactions at high temperatures in the ON and NeNa cycles. One star appears super O-poor; if the extension of the Na-O anticorrelation is confirmed, NGC 2808 might reach O depletion levels as large as those of M 13. This result confirms our previous findings based on lower resolution spectra (Carretta et al. 2003) of a large star-to-star scatter in proton capture elements at all positions along the RGB in NGC 2808, with no significant evolutionary contribution. Finally, the average metallicity for NGC 2808 is $[\text{Fe}/\text{H}] = -1.14 \pm 0.01$ dex ($rms = 0.06$) from 19 stars.

Subject headings: stars: abundances — stars: evolution — globular clusters: general — globular clusters: individual (NGC 2808)

1. Introduction

Since the pioneering work of Osborn (1971), a large body of evidence has accumulated indicating that globular clusters (GCs) are *not* mono-metallic populations, as far as the light elements (C, N, O, Na, Mg, Al) are concerned.

¹Based on data collected at the European Southern Observatory, Chile, during the FLAMES Science Verification.

²INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, 40127, Bologna, Italy. carretta@pd.astro.it, angela.bragaglia@bo.astro.it, carla.cacciari@bo.astro.it

While early studies on the light elements C, N, and carbon isotopic ratios showed that some kind of mixing was involved in RGB stars (C abundances declining with increasing stellar luminosities, C and N abundances anticorrelation among stars of same evolutionary phases, see Smith 1987 for a review), they could not explain why these variations were observed all the way down to unevolved stars where mixing is not supposed to play any role (e.g. the recent studies by Cannon et al. 1998; Harbeck et al. 2003; and references therein).

The Lick-Texas study of heavier elements (see Kraft 1994 and Sneden et al. 2004: S04, for complete references) in bright giants in several clusters showed that the [Na/Fe] and [O/Fe] ratios were anticorrelated: O-depletion was always accompanied by Na-enhancement, the stars in M 13 displaying the most severe variations. Whenever C and N abundances were available, N was anticorrelated with O, whereas a clear correlation existed between O and C abundances. This points to a redistribution of C,N,O in a H-burning CNO-cycle. The theoretical background presented by Denisenkov & Denisenkova (1990) and Langer et al. (1993) clarified that proton-capture reactions at high temperatures in the ON and NeNa cycles are involved in building up the observed pattern.

While these anomalies are markedly confined to the dense cluster environment (e.g. Gratton et al. 2000), the true site where CNO and NeNa cycles concur to form the observed abundance pattern is still a matter of debate. In fact, the same chains of p-captures (on C,N,O,Ne,Mg) may occur both in the H-burning shell of low mass ($< 1 M_{\odot}$) stars presently climbing up the RGB branch, and in the so called Hot Bottom Burning (HBB: Blöcker & Schönberner 1991, Boothroyd & Sackmann 1992) taking place in a prior generation of intermediate mass ($3 - 8 M_{\odot}$) stars in the asymptotic giant branch (IM-AGB) phase.

The first direct observations of O and Na abundances in dwarfs at the main-sequence turn-off in NGC 6752 (Gratton et al. 2001) and in 47 Tuc (Carretta et al. 2004) are a clearcut evidence that part of the observed Na-O anticorrelation must be primordially established, since these unevolved stars do not have either high enough temperatures in their cores for the required reactions or large enough convective envelopes to dredge up to the surface the products of p-capture reactions.

Here we present the results for Na and O obtained for 20 RGB stars in NGC 2808, observed during the FLAMES Science Verification. Carretta et al. (2003) exploited the MEDUSA mode of FLAMES at VLT-UT2 to uncover large star-to-star variations in Na abundances among 80 RGB stars in this cluster. In this Letter, we show that Na is anticorrelated with O, and we find preliminary evidence that in NGC 2808 the O-depletion in some stars could be as extreme as in M 13 super-O-poor stars.

2. Atmospheric parameters and abundance analysis

Twenty RGB stars with $V = 13.2 - 16.5$ were observed with the fiber-fed UVES Red Arm ($R = 47000$, spectral coverage of 200 nm, centered at 580 nm). Full details of the observations and data reduction, magnitudes, and coordinates can be found in Cacciari et al. (2004; C04). The S/N ratio varies a lot (the selection was optimized for studying mass loss, not for abundance analysis) and is shown in Figure 1 together with the target positions in the CMD.

Effective temperatures T_{eff} (from colors and the Alonso et al. 1999 calibration) are discussed in C04 and Carretta et al. (2003). Surface gravities $\log g$ were obtained from temperatures and bolometric corrections, using the distance modulus $(m - M)_V = 15.59$ (Harris 1996), and assuming that the stars have masses of $0.85 M_{\odot}$. The adopted bolometric magnitude of the Sun is $M(bol)_{\odot} = 4.75$. Equivalent widths (EW s) for Fe I, Fe II and Na lines were measured as described in Bragaglia et al. (2001). Details will be presented in a forthcoming paper. We derived the microturbulence velocity v_t by zeroing the slope of the abundances of Fe I vs EW s and the overall model metallicity was chosen using the Kurucz (1995) grid of model atmospheres with the overshooting option set on. Abundances of Fe I, Fe II and Na I were derived from the analysis of EW s (for Na from the doublets at 5682-88 Å and 6154-60 Å). O abundances were derived from spectral synthesis of the forbidden lines [O I] at 6300.31 and 6363.79 Å, after cleaning the observed spectra for telluric line contamination. The contribution of the weak, high excitation Ni line at 6300.34 Å, with the laboratory $\log gf$ recently measured by Johansson et al. (2003), is negligible (about 0.5 to 1.2 m Å) in the entire magnitude range. Reference solar abundances and atomic parameters for lines are those of Gratton et al. (2003). Adopted parameters and derived abundances are listed in Table 1.

The ionization equilibrium FeII/FeI is good: on average, $[\text{Fe}/\text{H}]_{\text{II}} - [\text{Fe}/\text{H}]_{\text{I}} = 0.00 \pm 0.03$, $rms = 0.15$ dex (19 stars: for star 34013, with $S/N \sim 20$, measurements of EW s were unreliable and this star was dropped from further discussion). Excluding the coolest star (50761), there seems to be a slight trend for increasing the FeII-FeI difference with decreasing T_{eff} . While this could hint to possible departures from LTE (overionization), the good agreement of Fe I abundances all over the sampled range in T_{eff} argues against an underestimate of $[\text{Fe}/\text{H}]$ abundances. Another possibility is that the structure of the atmospheres for coolest giants is not well reproduced by models of the Kurucz grid (see Dalle Ore 1993). No noticeable trend of derived abundances as a function of the excitation potential is discernible. This supports the adoption of the Alonso et al. temperature scale, as found also by Ivans et al. (2001). Estimates of typical errors in T_{eff} , $\log g$, $[\text{A}/\text{H}]$ and v_t are 70 K, 0.1 dex, 0.1 dex and 0.1 km s^{-1} , respectively. When combined to errors in the measurement

of EW s, they translate into a total (internal) error of about 0.08 dex in $[Fe/H]$ and $[Na/Fe]$ and 0.13 dex in $[O/Fe]$.

Average values for NGC 2808 are $[Fe/H]I = -1.14 \pm 0.01$, $rms = 0.06$ dex and $[Fe/H]II = -1.14 \pm 0.03$, $rms = 0.13$ dex. This is the first determination of the iron abundance based on modern high resolution spectra for this cluster.

3. Results and discussion

Derived abundances of Na and O are plotted in Figure 2. $[O/Fe]$ ratios were referred to Fe II; $[Na/Fe]$ ratios are corrected for departures from LTE as in Gratton et al. (1999), and are referred to Fe I abundances. This is the first study to unveil the existence of the Na-O anticorrelation in this cluster. In Carretta et al. (2003), we pointed out the large spread observed in Na abundances at all luminosities along the RGB; however, the MEDUSA spectra (acquired to study the mass loss) were centered on the Na D or $H\alpha$ features and they did not contain O lines.

Here we show that also O abundances are very different among stars at the same position along the RGB. We show in Figure 3 the strengths of the forbidden $[O\ I]$ line at 6300 Å in 3 pairs of stars with similar atmospheric parameters, yet quite large difference in the Na and O content, from just above the RGB-bump (where only upper limits could be derived for O; nevertheless, stars 42886 and 32685 differ by 0.5 dex in Na abundances), to the upper RGB and RGB tip. From this Figure it is clear that large star-to-star scatter in *both* O and Na abundances does exist among red giants in NGC 2808.

In Figure 2 we also compare our data in NGC 2808 to similar ones for M 5 (Ivans et al. 2001) and for M 13 (S04), after an adjustment for the offset in the adopted solar O abundance (0.14 dex). The comparison with M 5 (a cluster with almost the same mean $[Fe/H]$ as NGC 2808, see e.g. Carretta and Gratton 1997) shows that the Na-O distributions are grossly similar. In the high-O, low-Na regime, stars observed by Ivans et al. (2001) have mostly spectra with $S/N > 60$, whereas only a $S/N \sim 30$ could be reached for our 2 stars of NGC 2808, giving only upper limits for O abundances. However, the impression is that in the O-poor, Na-rich part of this diagram the two distributions might be somewhat different, with NGC 2808 reaching larger O depletions. For the most O-poor star (50119), even with $S/N \simeq 70$, the $[O\ I]$ line at 6300.31 Å is vanishingly small and only an upper limit could be assigned. The comparison with M 13, the archetype for extremely O-depleted stars, seems to show that a similar degree of O-depletion is possibly reached also in NGC 2808. Admittedly, this is based on only one star. Higher quality spectra, purposely acquired, should be taken

to verify this issue.

The recent finding of a clear Na-O anticorrelation among unevolved stars in NGC 6752 (Gratton et al. 2001) and in 47 Tuc (Carretta et al. 2004) strongly points out that variations in these elements must be due to H-burning at high temperature in stars able to dredge-up and then eject their O-poor, Na-rich matter. In fact, because dwarf stars are unable to manage either of these requirements, an external origin for the Na and O abundance pattern must be necessarily accepted. IM-AGB stars are found to be good candidates (see e.g. Ventura et al. 2002).

A certain amount of further modifications as the star climbs up the RGB was postulated, since the lightest elements, like carbon, show a decrease as a function of stellar luminosity. For Na and O, the only clear evidence was found for M 13, where a shift in the average abundances was noted for the brightest red giants (Pilachowski et al. 1996; Kraft et al. 1997), above $\log g \sim 1.0$. However, recently S04 found that the anticorrelation between O and Mg isotopic ratios in M 13 is very similar to that in NGC 6752 (Yong et al. 2003), where the primordial pattern of chemical anomalies is well established. On this basis, S04 concluded that also in M 13 the extreme O-depletions are likely originated in IM-AGB stars. Apparently, the observed Na-O pattern in NGC 2808 is not very different from the marked anti-correlation in M 13. The implication is that also in NGC 2808 we are seeing the results of a pattern of abundances already established by a first generation of IM-AGB stars (see e.g., Parmentier 2004; D’Antona & Caloi 2004). An evolutionary contribution, if any, is nevertheless very small in this cluster (Carretta et al. 2003).

Is there any link between chemical inhomogeneities and global properties in GCs? This remains presently an unsolved issue, but this study in NGC 2808 may allow to add another piece to the puzzle. In fact, NGC 2808 and M 13 have a rather different HB morphology, in spite of their similar $[\text{Fe}/\text{H}]$. NGC 2808 is the most famous example of bi-modal HB: almost 1/4 of its HB stars lies in the blue part of the CMD, while presenting a well populated, stubby red HB. Yet, our findings seem to show O-depletions as large as in M 13, where only a long blue HB is seen. On the other hand, NGC 6752 (whose blue HB is very similar to the one of M 13) does not show (Yong et al. 2003) super O-poor stars as observed in M 13 and, likely, in NGC 2808.

Clusters like M 5 and M 3 are, in this respect, more similar to NGC 6752. The Na-O anticorrelation in these clusters does not reach the extreme values of M 13 (S04; Ivans et al. 2001). Moreover, NGC 6752 is a post-core collapse system (Harris 1996), whereas the other quoted GCs have different, but not *extremely* different, concentration parameters. Still, variations in Na and O are observed also in the much less massive and loose cluster Pal 5 (Smith et al. 2002), presently leaving a trail of its stars into the galactic field due to

disruptive processes like tidal shocking.

In summary, abundance inhomogeneities in elements produced by p-capture fusions at high temperature are observed in GCs independently of (i) total mass and concentration, (ii) galactic (disk or halo) population, (iii) overall metallicity, and (iv) HB morphological type. At face value, the Na-O anticorrelation is found in every cluster surveyed insofar, despite the large differences in global properties. Following Occam’s razor, this might imply that we are seeing the outcome of a process intimately related to dense aggregates, maybe intrinsically connected to their own formation process. This is supported by the lack of such a behaviour in field stars (see Gratton et al. 2000).

What to do next? We are quite confident about the *shape* and meaning of the Na-O anticorrelation in term of products of p-capture reactions in the ON and NeNa cycles. A step forward would be now to study the *distribution function* of the anticorrelation, using high quality spectra of large samples (~ 100) of stars along the RGB in several clusters spanning a variety of parameters (age, metallicity, HB morphology, etc.), to look for any possible connection unnoticed until now due to the paucity of samples. This is a project we are currently working on using the FLAMES multi-object spectrograph at ESO-VLT.

The authors thank R.G. Gratton for invaluable suggestions and discussion, the ESO staff for the observations and the preliminary data reduction, and G. Mulas for performing a more detailed data reduction.

REFERENCES

- Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
- Blöcker, T., & Schönberner, D. 1991, A&A, 244, L43
- Boothroyd, A. I., & Sackmann I-J. 1992, ApJ, 393,L21
- Bragaglia, A., et al. 2001, AJ, 121, 327
- Cacciari, C., et al. 2004, A&A, 413, 343
- Cannon, R. D., Croke, B. F. W., Bell, R. A., Hesser, J. E., & Stathakis, R. A. 1998, MNRAS, 298, 601
- Carretta, E., & Gratton, R.G. 1997, A&AS, 121, 95
- Carretta, E., Bragaglia, A., Cacciari, C., & Rossetti, E. 2003, A&A, 410, 143

- Carretta, E., Gratton, R.G., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004, *A&A*, 416, 925
- D’Antona, F., & Caloi V. 2004, *ApJ*, in press (astro-ph/0405016)
- Dalle Ore, C. 1993, Ph.D. Thesis
- Denisenkov, P. A., & Denisenkova, S. N. 1990, *Soviet. Astron. Lett.*, 16, 275
- Gratton, R. G., et al. 2001, *A&A*, 369, 87
- Gratton, R. G., Carretta, E., Claudi, R., Lucatello, S., & Barbieri, M. 2003, *A&A*, 404, 187
- Gratton, R. G., Carretta, E., Eriksson, K., & Gustafsson, B. 1999, *A&A* 350, 955
- Gratton, R. G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, *A&A*, 354, 169
- Harbeck, D., Smith, G. H., & Grebel, E. K. 2003, *AJ*, 125, 197
- Harris, W. E. 1996, *AJ*, 112, 1487
- Ivans, I. I., Kraft, R. P., Sneden, C., Smith, G. H., Rich, R. M., & Shetrone, M. D. 2001, *AJ*, 122, 1438
- Johansson, S., Litzèn, U., Lundberg, H., & Zhang, Z. 2003, *ApJ*, 584, L107
- Kraft, R. P. 1994, *PASP*, 106, 553
- Kraft, R. P., Sneden, C., Smith, G. H., Shetrone, M. D., Langer, G. E., & Pilachowski, C. A. 1997, *AJ*, 113, 279
- Langer, G. E., Hoffman, R., & Sneden, C. 1993, *PASP*, 105, 301
- Osborn, W. 1971, *Observatory*, 91, 223
- Parmentier, G. 2004, *MNRAS*, in press (astro-ph/0403234)
- Pilachowski, C. A., Sneden, C., Kraft, R. P., & Langer, G. E. 1996, *AJ*, 112, 545
- Smith, G. H. 1987, *PASP*, 99, 67
- Smith, G. H., Sneden, C., & Kraft, R. P. 2002, *AJ*, 123, 1502
- Sneden, C., Kraft, R. P., Guhathakurta, P., Peterson R. C., & Fulbright, J.P. 2004, *AJ*, 127, 2162

Ventura, P., D’Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215

Yong, D., Grundahl, F., Lambert, D. L., Nissen, P. E., & Shetrone, M. D. 2003, A&A, 402, 985

Table 1. Adopted parameters and derived abundances.

Star ID	S/N	T_{eff} K	$\log g$ dex	v_t km s ⁻¹	n	[Fe/H]I dex	σ dex	n	[Fe/H]II dex	σ dex	n	[Na/Fe] dex	σ dex	[O/Fe] dex
10201	45	4717	2.02	1.20	51	-1.06	0.13	8	-1.21	0.05	3	+0.23	0.06	-0.05
13983	40	4826	2.17	0.60	33	-1.08	0.08	5	-1.09	0.13	2	+0.45	0.12	-0.54
32685	30	4788	2.03	0.83	34	-1.15	0.09	5	-1.41	0.07	2	+0.48	0.10	< -0.24
34013	20	5110	2.51	0.80	29	-0.89:	0.21							
37872	120	4015	0.71	1.68	96	-1.10	0.11	14	-1.06	0.08	4	+0.44	0.07	-0.34
42886	30	4791	2.14	0.85	47	-1.16	0.14	4	-1.38	0.10	2	-0.17	0.13	< +0.47
43217	30	4916	2.41	0.80	33	-1.00	0.12	7	-1.17	0.13	1	-0.31		< +0.37
46099	80	4032	0.76	1.72	60	-1.18	0.12	10	-1.19	0.12	2	+0.17	0.03	+0.25
46422	100	3943	0.52	1.85	95	-1.17	0.12	14	-1.08	0.09	3	+0.12	0.11	+0.23
46580	65	4051	0.74	1.68	89	-1.15	0.11	15	-1.03	0.13	4	+0.33	0.05	+0.10
47606	110	3839	0.44	1.66	85	-1.12	0.14	14	-1.14	0.16	4	+0.09	0.05	+0.20
48609	110	3846	0.44	1.78	58	-1.22	0.12	8	-1.11	0.13	3	+0.07	0.09	+0.20
48889	85	3943	0.52	1.80	99	-1.15	0.15	13	-1.22	0.12	4	+0.64	0.13	-0.07
50119	70	4166	0.93	1.73	119	-1.08	0.15	18	-1.21	0.13	4	+0.53	0.03	< -1.00
50761	120	3756	0.31	1.75	81	-1.22	0.12	10	-0.81	0.07	4	+0.15	0.12	-0.29
51454	120	3893	0.51	1.65	90	-1.26	0.11	14	-1.11	0.13	4	+0.21	0.07	+0.13
51499	85	3960	0.57	1.70	104	-1.25	0.10	18	-1.24	0.12	4	+0.17	0.10	+0.29
51983	95	3855	0.47	1.77	71	-1.15	0.11	13	-1.16	0.12	4	+0.53	0.09	-0.17
53390	60	4426	1.43	1.30	106	-1.12	0.10	19	-1.14	0.13	4	+0.00	0.09	+0.40
56032	70	4045	0.87	1.70	103	-1.10	0.10	17	-0.99	0.12	4	+0.06	0.09	+0.19

^an is the number of measured lines.

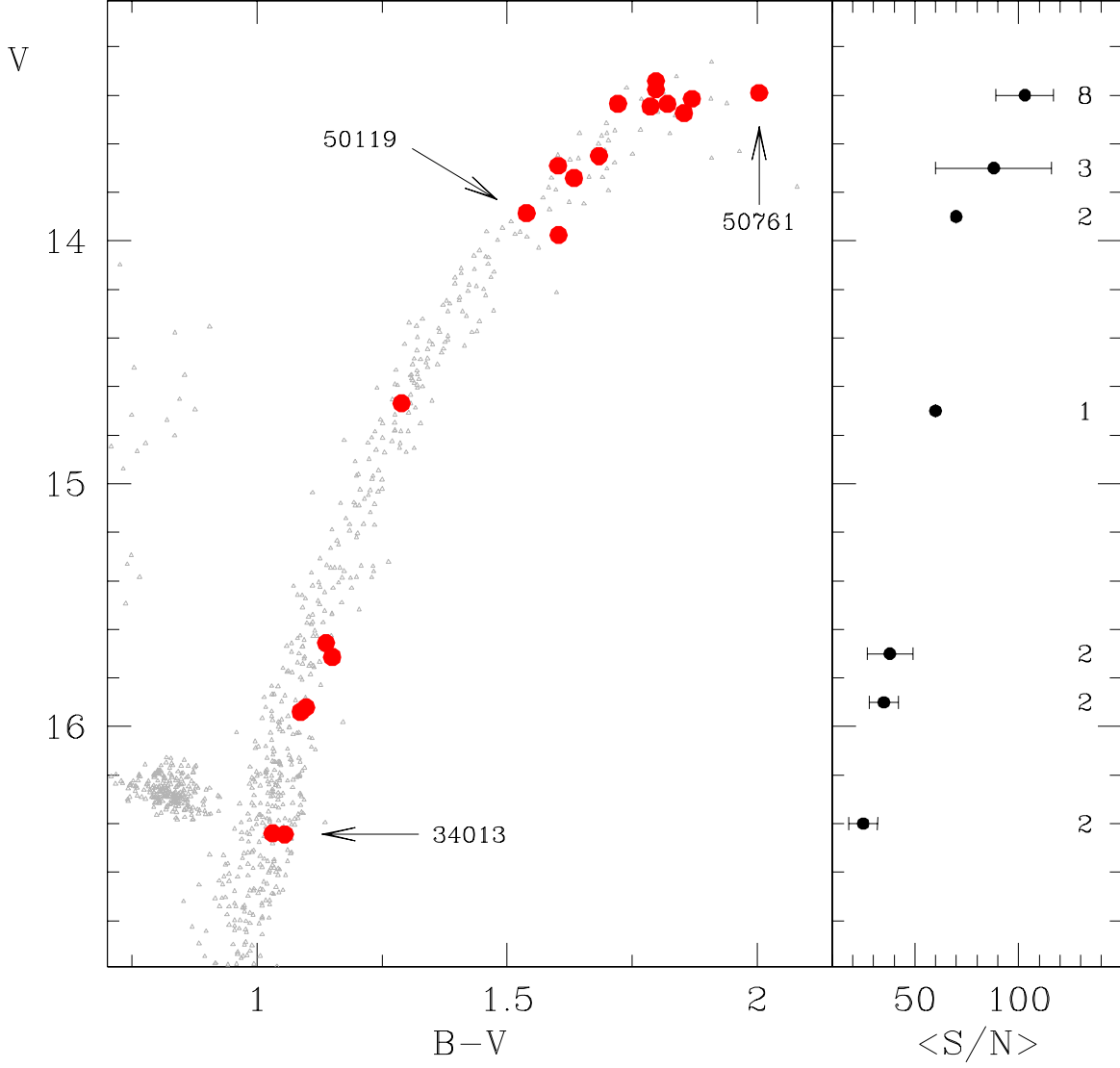


Fig. 1.— Observed stars are indicated by larger filled circles on the $V, B - V$ CMD of NGC 2808 (Piotto et al., priv.comm.). The right panel shows the average S/N at different magnitude levels, and numbers indicate how many stars were averaged each time. The coolest star is indicated, as well as the ones with the lowest S/N (34013, dropped from discussion) and with the lowest O abundance (50119).

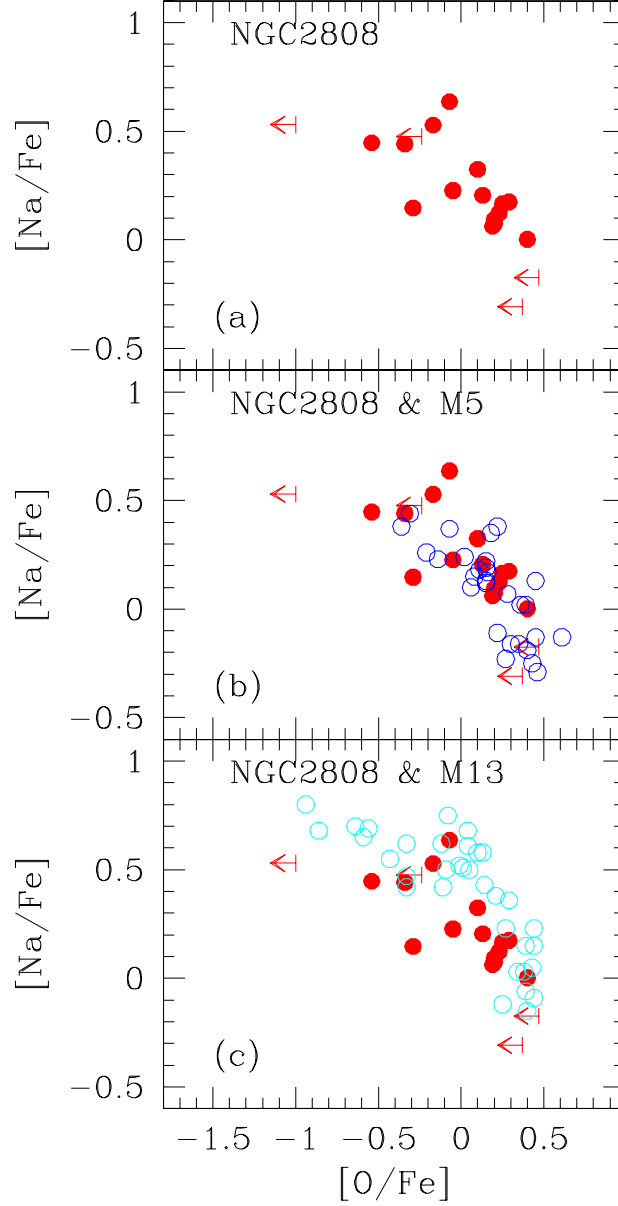


Fig. 2.— $[\text{Na}/\text{Fe}]$ vs $[\text{O}/\text{Fe}]$ ratios in red giants of NGC 2808 (upper panel). Filled circles are effective detections. Upper limits in O are indicated by arrows. Middle panel: the same, with overimposed RGB stars in M 5 (Ivans et al. 2001; open circles). Lower panel: the same, with overimposed RGB stars in M 13 (Sneden et al. 2004; open circles).

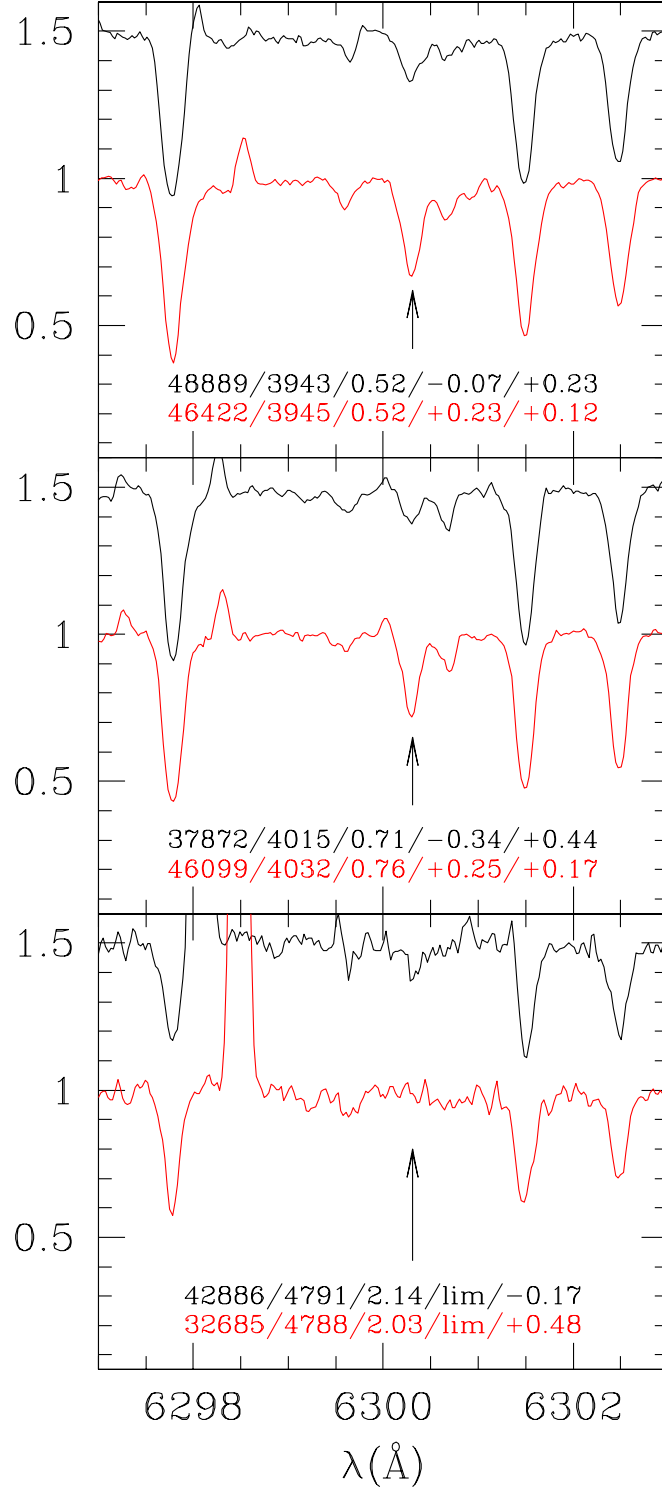


Fig. 3.— Comparison of observed spectra of 3 pairs of RGB stars in NGC 2808. Arrows indicate the [O I] 6300.31 Å forbidden line. Each pair has similar atmospheric parameters, as indicated by the labels, that give star id, T_{eff} , $\log g$, [O/Fe] and [Na/Fe].